METHOD OF IMPROVING EFFICIENCY OF COMBINED CYCLE POWER PLANTS

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

METHOD OF IMPROVING EFFICIENCY OF COMBINED CYCLE POWER PLANTS

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LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2.4 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
http://www.energy.ca.gov/research/index.html.

Method of Improving Efficiency of Combined Cycle Power Plants

EISG Grant # 00-28

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Introduction

Large (>200 MW) gas turbine combined cycle power systems are the primary choice in California for new utility-scale power generation facilities. The cost of fuel for these systems is over 80% of their operating expense. While system efficiencies are often over 50%, any further improvement in engine efficiency reduces both the cost of the power and the emissions generated per megawatt-hour. Engineers note that turbine exhaust backpressure is a significant source of efficiency loss in gas turbine combined cycle (GTCC) power plants. Poor aerodynamics in the transition section between the gas turbine and the heat recovery steam generator (HRSG) is the source of this backpressure.

The cost of electricity generated by GTCC power plants is dependent on the heat rate of the engine system and cost of natural gas. If the heat rate is reduced (less fuel is used to generate each megawatt-hour) the cost to produce electricity will decline. The cost of electricity generated by GTCCs is in the range of 3.0 to3.7 cents/kWh depending on system efficiency. A 0.5% increase in system efficiency (for the most efficient systems) could reduce electricity costs by 0.028 cents/kWh, saving Californians up to $18 million per year. Savings are based on all GTCCs in operation or under construction in the state being fitted with the ejector-diffuser.

Dynamic pressure recovery in turbine exhaust nozzles, which are subsonic, is limited by the onset of flow separation at an area ratio of the order of 1.5 to 1. By adding an ejector-diffuser, the total expansion ratio can be doubled without flow separation. Additionally, the ejector-diffuser can function as a suction pump that can be used to modify the boundary layer separation experienced in the transition section of the HRSG. The approach taken by this project was to quantify the benefits of the ejector-diffuser installed in the flow path between the exhaust diffuser of a straight-through gas turbine and the HRSG of a combined cycle power plant. The ejector-diffuser improves the aerodynamics and thereby reduces the backpressure on the gas turbine engine. Basically, the innovation is an annular plenum with ports to the exhaust flow. It surrounds the conventional exhaust diffuser. No air or steam flows through the plenum. The researcher proposed using computational fluid dynamic (CFD) modeling to model the ejector-diffuser in the flow duct in an effort to increase the stable expansion ratio and to improve the flow distribution. Prior one-dimensional analysis indicated savings on the order of 0.5 percent. The purpose of this study was to quantify accurately the savings, using state-of-the-art CFD analysis incorporating three-dimensional viscous flow, and separation phenomena.

Objectives

The goal of this project was to determine the feasibility of increasing GTCC efficiency by 0.5% using an ejector-diffuser to reduce the pressure losses in the transition section between a gas turbine exhaust diffuser and the heat recovery steam generator. The researcher established the following project objectives:

1. Demonstrate a reduction in backpressure at the gas turbine exit plane of 4 inches of water when compared with the conventional turbine to HRSG transition section (typically 12 to 16 inches of water). Backpressure reduction leads directly to engine efficiency improvement.
2. Demonstrate the potential for stabilizing the boundary layer in the transition section of the HRSG with the new technology. Flow separation should be reduced or eliminated to increase the turbine adiabatic expansion ratio. An increased expansion ratio leads to lower turbine backpressure.
3. Demonstrate an overall improvement in efficiency of 0.5% or more.

Outcomes

1. Calculations demonstrated backpressure reduction at the exit plane of the gas turbine to be over 4 inches of water.
2. The researcher demonstrated that the flow path more closely followed the duct walls resulting in an increase in the adiabatic expansion ratio by a factor of two.
3. The researcher demonstrated a 0.5% engine efficiency improvement.

Conclusions

1. A properly designed ejector-diffuser can significantly improve the flow characteristics into the transition duct of a combined cycle gas turbine system. The diffuser increases the adiabatic expansion ratio by a factor of 2, which allows the nozzle exit plane pressure to decrease by about 4 inches of water.
2. The addition of a suction surface to the transition section causes the flow to follow the upper surface of the duct and therefore increase the turbine adiabatic expansion ratio. More work is required to investigate duct changes to induce the flow to turn the corner in the transition duct.
3. All gas turbine engines are sensitive to nozzle exit-plane backpressure. A 4-inch drop in exit pressure can produce a 0.5 percent increase in engine efficiency in the GE Frame 7FA engine. Ejectors can produce high levels of noise. This adds to the problem of noise reduction in any combined cycle plant. The researcher did not comment on this issue.
4. The researcher did not estimate the incremental capital and operating costs of adding ejectors. The device appears to be relatively simple to implement.

Benefits to California

If the ejector-diffuser concept demonstrated in this project was applied to all large gas turbine combined cycle power plants operating or under construction in California, ratepayers would save from $6 million to a maximum $18 million per year. Maximum beneficial savings are based on 8000-hour annual operation. A GTCC typically runs less than 4000 hours/year. Savings would increase as more GTCCs are licensed in the state. Air quality would improve because less fuel would be consumed to produce the same amount of electricity. With lower demand for natural gas, prices for that commodity could be less volatile.

Recommendations

A physical demonstration is required before significant interest can be generated in the optimized ejector-diffuser. The PA recommends a cold test in a model test facility as a first step of verifying the CFD model results. Upon successful completion of that test, the researcher should work with a real project and perform a hot test. The potential benefits of this research are great enough to continue public funding of the project through the cold test phase. At that point an HRSG manufacturer or a turbine manufacturer should begin to participate in the hot testing and commercialization of this technology.

The researcher should estimate the cost to build and operate an ejector-diffuser in a GTCC system.

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the PIER/EISG project development methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The researcher plans to license the ejector-diffuser technology for commercialization. The PA recommends the researcher present his findings at a major gas turbine technical conference to identify interested partners. Market size in California could be in the range of 10 to 15 units per year for new power plants. "One unit" would be a typical 250 MW GTCC. Some sites use multiple units. Worldwide the market would be considerably larger.

Engineering/Technical

This project proved the feasibility of using an ejector-diffuser to increase the efficiency of a gas turbine engine by 0.5% when running in a combined cycle mode. Actual testing is required to demonstrate benefits in a real combined cycle system. In addition the Program Administrator recommends analysis be performed to determine noise levels.

Legal/Contractual

No legal issues were reported. The researcher applied for and received a patent for this technology. The patent number is 5,632,142. The researcher has written a preliminary licensing agreement.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental. The researcher should determine the additional noise, if any, at the GTCC site.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

The researcher identified potential licensees for the ejector-diffuser. These include HRSG manufacturers, turbine manufacturers and packagers, and owners of new and operating combined cycle power plants. No production readiness plans have been developed. When performing actual tests of the ejector-diffuser the researcher should work with a commercial firm that is in HRSG business. This should lead to a commercialization relationship.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system sIncreased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. If the ejector-diffuser were applied to all large gas turbine combined cycle power plants in California built or under construction the cost savings could be as high as $18 million per year. This savings is calculated in the following manner.

GTCCs produce electricity for ~$0.035/kWh and 80% of that is fuel cost.

Fuel cost in a GTCC per kWh is $0.028/kWh.

Based on current system efficiencies of 50% a 0.5% improvement in fuel efficiency is about a 1/100 improvement or $0.00028/kWh.

Annual savings for a typical 250 MW unit = 250 MW x 8000 hours/y x $\$2.8x10^{-4}$/kWh = $560,000/y.

About thirty-two, two hundred and fifty MW units are built or licensed to be built and under construction in the state.

32 units x $560,000 = $17.9 million.

This is a maximum savings estimate. Not all units would be fitted with the ejector-diffuser and most GTCC units do not run 8000 hours/year. A more realistic saving to ratepayers would be closer to $6 million with the current fleet of GTCC units.

Other benefits include less air pollution, and perhaps, less volatility in the price of natural gas due to reduced demand.

Program Administrator Assessment

After taking into consideration: (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

METHOD OF IMPROVING EFFICIENCY OF COMBINED CYCLE POWER PLANTS

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgement Page

I would like to take the opportunity to thank the AEA TECHNOLOGY, ENGINEERING SOFTWARE, INC. Company, particularly Dan White and Dr. Rob Blumenthal for their guidance over the duration of the Project. All of the work done for this study was accomplished with AEA Technologies CFX 5.5.1 computer program. The code is very robust and accurate. But like most things worth doing, one has to pose the right questions to get meaningful answers. Dan and Rob demonstrated great knowledge of the code and the physics of what I was studying. Their patience and tutoring through the process was absolutely necessary for a successful out come.

My first encounter with Computational Fluid Dynamics (CFD) dates back to the late 60's. By the early 70's, Dr Hans Mark, Secretary of the US Air Force, declared that wind tunnels were in the process of becoming superfluous. From the industrial giants to the universities laboratories, the aerospace community protested that he had set back test cell funding ten years of more. Fortunately, Congress didn't take him too seriously.

The CFD codes that AEA Technology and others now have are close to threatening test cell research. Clearly the need will always be there for physical testing but CFD will significantly reduce the amount of physical testing that is required

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Abstract

Turbine exhaust backpressure is a significant source of efficiency loss in gas turbine fired power plants. Dynamic pressure recovery in turbine exhaust nozzles, which are subsonic, is limited by the onset of flow separation at an area ratio of the order of 1.5 to 1. By adding an Ejector-Diffuser (E-D) (Patent No. 5,632,142) the total expansion ratio can be doubled without flow separation. Additionally, the Ejector-Diffuser can function as a suction pump that can be used to modify the boundary layer separation experienced in the transition section of the Heat Recovery Steam Generator (HRSG). This Project was designed to test various configurations of the E-D against current design practices. For a GE frame 7FA, a doubling of the expansion ratio will result in a lowering of the nozzle exit pressure by about 4 inches of water. The result is an efficiency improvement of the order of 0.5 percent.

This project employed Computational Fluid Dynamic (CFD) analysis to study conventional and modified geometry's in turbulent, 3-D, Steady state, and viscous flow simulation. Prior to the Project, the only test runs were made with a few 1/12th scale model simulation tests "piggy backing" on engineering test of a conventional HRSG installation. There was not time to make significant changes, which the CFD analysis afforded.

The first runs were inconclusive as both the conventional (base) case and the original E-D configurations suffered from partial flow separation in the diffuser exit. The next two modifications of diffusers, which would be much simpler to manufacture, showed a definite improvement in dynamic head recovery of slightly more than 4 inches of water.

Executive Summary

1. Introduction:
Pro-forma analyses of projected expenses of a Frame 7FA combined cycle gas turbine fired base load plant indicate that fuel cost make up close to 80 percent of the recurring cost of operation. With this burden, the power industry is constantly searching for cost effective improvements in efficiency. The Ejector-Diffuser (E-D), (Patent No. 5,632,142) has the potential of providing a cost effective means of improving efficiency. The E-D needed to be tested to quantify its pressure recovery ability in a real or simulated environment. Real field-testing would be prohibitively expensive. The next best thing from a proof of principle is Computational Fluid Dynamics (CFD), which is computer simulation. CFD has proved itself to provide an excellent simulation of flow phenomena under the conditions encountered in power plants.

2. Project Objectives:
Objective 1: Demonstrate an improvement the flow characteristics in the exhaust stream of the gas turbine in a combined cycle power plant. The result would be a noticeable reduction in flow turbulence and a smoother fuller flow in the ductwork. Objective 2: Demonstrate the potential for stabilizing the boundary layer in the transition section of the HRSG by using the E-D for boundary layer sucking to get the flow to turn the corner of the upper section of the transition section before it separates.
Objective 3: Demonstrate an overall improvement in efficiency of .5% or more.

3. Project Outcomes:
The E-D definitely achieved the performance improvement of Objective 1. More work needs to be done to prevent flow separation in the transition duct. The improvement in flow characteristics is adequate to achieve the .5% efficiency goal.

4. Conclusions:
The E-D will achieve the efficiency gains needed to be considered for development.

5. Recommendations:
A follow-on study should be initiated with a potential fabricator such as an HRSG manufacturer to work on fabrication economics and development requirements to convince the industry of the viability of the E-D concept.

6. Public Benefits to California:
The higher the efficiency the lower the emissions for the power produced. Power producers utilizing this technology will be more competitive.

Introduction

Background and Overview
1) Project Objectives

The main objective of this project is to quantify a means of reducing the pressure losses in the transition section between the exhaust diffuser of a straight-through gas turbine and the Heat Recovery Steam Generator (HRSG) of combine cycle power plant installations by

Computational Fluid Dynamic (CFD) modeling. The concept to be modeled will incorporate an Ejector-Diffuser in the flow stream, which can be used to increase the stable expansion ratio obtainable and to improve the flow distribution in a typical HRSG transition duct. One-dimensional analysis indicates savings in the order of 0.5 percent. The purpose of this study is to quantify the savings using state of the art CFD analysis incorporating three dimensional, viscous, and separation phenomena. The energy savings achieved here are additive to other cycle improvements being made. The total benefit will depend on incorporation of the technology.

(2) Energy Problem Targeted

Many parameters affect the output and efficiency of gas turbine driven power plants. Gas turbine engine designers have steadily improved the basic cycle efficiency with ever-higher combustion temperatures and more efficient internal aerodynamic designs. Additionally, systems integrators have incorporated equipment to mitigate the effects of adverse inlet conditions such as minimum pressure loss filtration, flow straightening, and inlet chillers. In a typical combined cycle installation the backpressure is of the order of 12 to 16 inches of water, which translates into an efficiency loss of the order of two percent. Exhaust diffusers recover some of the dynamic pressure and exhaust duct design and efficient heat exchanger design in the Heat Recovery Steam Generators (HRSG) mitigate static pressure losses of combined cycle systems. However, the exhaust stream pressure losses continue to be the major source of output and efficiency loss at the integrated system level.

3) Impact on Energy Problem

A more efficient plant cycle directly equates to a reduction in the amount of fuel required per kW. This in itself is a benefit to the environment. In an unregulated market, competition should force some of the saving into the price structure.

4) State-of-the-Art

Engine manufacturers are now doing more than they did 5 years ago when the diffusers ended almost at the after body center bearing support. Nearly all the large "F" series engines expand the engine diffuser out to about 1.5 to 1 with respect to the bearing support station. Some have added an aerodynamic center body nozzle plug which smoothes the center body core turbulence. In some installations engine manufacturers supply spool piece which transitions from a round to square or rectangular cross section to provide as full a flow as it enters the HRSG transition section.

When the flow enters the HRSG transition section the flow typically separates off the upper wall and because of the abrupt change in direction, usually about 45 degrees. The HRSG needs an even distribution of flow to produce steam efficiently. To do this, large perforated plates are put in the flow stream to even it out. This is the most likely source for potential pressure recovery in the exhaust stream.

There is no direct competitor to this product. The closest technology is the "Flow Enhancer" designed by Consultants in Engineering Acoustics used on the LM2500 series Gas Turbine generator sets. However this is a complex set of engineered shapes installed in the turbine exhaust collector box designed to soften the insult of the 90° turn which the exhaust takes within one diameter of the turbine nozzle. This is successfully marketed to plant owners for $5,000 per installed MW. This is a good indication that efficiency will sell and with the deregulated market where market share is becoming cost driven, efficiency becomes even more important. This technology, while proven, is still meeting resistance because of the concerns of introducing complex materials in the gas stream, which could potentially come loose and cause foreign object damage.

5) Concept Feasibility Issues

To date a couple of sub-scale similarity model tests have been run piggy back on engineering tests for a conventional HRSG installation. The ability to achieve flow reattachment in the Ejector-Diffuser was demonstrated. However, the down stream flow components were not properly designed to demonstrate projected pressure recovery. Due to model and budget constraints in the flow model testing, the proper configuration was never achieved. The use of Computational Fluid Dynamic (CFD) modeling will allow modifications not available in sub-scale similarity tests. The CFD model will more properly simulate a real turbine exhaust reaction to a better pressure recovery.

We are testing Ejector-Diffusers in a range not seen in conventional applications. In altitude test facilities the exhaust gases in modern turbofan engines usually have a significantly higher dynamic head of the order of Mach No equal to 0.7. What we are looking for is recovering a few more inches of H_2O in an exhaust flow in the Mach No = .3 to .4 range.

6) Proposed Innovations

The Ejector-Diffuser (Patent No. 5,632,142) is a custom-engineered duct enclosure connecting the exhaust from Gas Turbine Fired Power Plant to the downstream exhaust ducting or the transition piece of a Heat Recovery Steam Generator. (Figure 1, E-D Configuration) The Ejector-Diffuser consists of a plenum attached to the gas turbine diffuser exit and having a duct on centerline with the turbine exhaust nozzle but somewhat down stream of approximately twice the area of the turbine diffuser which exits the plenum and flows into the down steam ducting. In simplest terms, it is a closed jet pump. Each installation will have to be analyzed and optimized depending on the engine model and physical space available.

The key to the engine performance improvement is that the flow at the exit of the power turbine is subsonic and any change in exhaust plan pressure will affect the work in the power turbine. This means that any pressure recovery will manifest itself in a reduction in turbine exhaust backpressure, which we can directly correlate to an increase in power output at the same fuel consumption or a lesser fuel consumption for the same power output. The increase in gas turbine output comes with a slight decrease in exhaust gas temperature, which will temper the steam cycle performance. However, improvements in the high efficiency gas turbine cycle will more than offset losses in the less efficient steam cycle. Additionally, the compactness of the Ejector-Diffuser means that it should be particularly attractive to retrofit in existing installations. The efficiency advantage is dependent on the particular integrated system but will be sufficient to cover a payback of the modest installation cost in less than two years. Additionally, the compactness of the Ejector-Diffuser means that it should be particularly attractive as a retrofit in existing installations.

Ejector-Diffusers have been used in aerospace propulsion test facilities to recover the dynamic pressure of the exhaust stream of air breathing and rocket propulsion devices where it is necessary to simulate a low-pressure ambient environment. Because of the esoteric nature of altitude simulation test facilities, little has been published on this use of Ejector-Diffusers outside of the testing community. The classic Ejector-Diffuser is also known as a jet pump in industry and finds many uses from steam ejectors to fluid or slurry pumps. Interestingly, symposia on jet pumps and ejectors will not even mention altitude test facility use of ejectors; and of course, no mention of applying ejectors to power applications prior to this patent.

To avoid flow separation in the turbine exhaust diffusers, area ratios are usually limited to 1.5:1. By adding an ejector system at the exhaust plane of the gas turbine diffuser the total expansion ratio can be increase to 2.5:1 or greater without flow separation. The ejector is not as efficient as a classic diffuser; however, it is much more compact and can thus achieve additional pressure recovery without separation in the limited space available. The energy loss in the ejector should be more than offset by the additional pressure recovery and improved flow conditioning of the exhaust stream as it enters the remaining components.

The Ejector-Diffuser is by definition a pump. In addition to the increased diffusion, there is the possibility of doing some boundary layer control on the upper wall of the HRSG transition to prevent flow separation. Flow separation on a surface is caused by the inability of the boundary layer to remain attached to the wall. By sucking on the boundary layer through a series of small holes in the upper wall of the HRSG, the flow should remain attached and a more orderly expansion will occur. The static pressure in the in the ejector plenum is less than in the HRSG and can be used as a source for the boundary layer suction control though a properly designed manifold system.

7) Primary Tasks

The objective of this project is to quantify the potential pressure recovery improvements achievable by incorporating an Ejector-Diffuser in the exhaust stream of a gas turbine fired power plant. Utilizing a state of the art turbulent, 3-D, steady state, and viscous flow simulation will accomplish this by Computational Fluid Dynamic (CFD) analysis of exhaust configurations using current industry practice and selected modifications using Ejector-Diffuser technology. The product is this written report including tabular and graphical results.

The tasks were as follows:

Task 1: Define the Standard Configuration
Select an existing Turbine/HRSG configuration and define the steady-state parameters and geometry to be used.

Task 2: Set Up & Run Standard Configuration

Create CAD model; Create CFD Mesh; specify fluid properties, boundary conditions, solver parameters, etc.; run CFD code; post processing.

Task 3: Set Up & Run 1st E-D Configuration. Same as Task 2 with 1st E-D Configuration

Task 4: Set Up & Run 2nd E-D Configuration. Same as Task 2 with 2nd E-D Configuration

Task 5: Set Up & Run 3rd E-D Configuration. Same as Task 2 with 3rd E-D Configuration incorporating boundary layer control

Task 6: Set Up & Run 4th E-D Configuration. Same as Task 2 with 4th E-D Configuration incorporating boundary layer control

Task 7: Produce Final Report

8) Market Connection

Energy Constructs will form a strategic alliance with another company or companies. At a minimum the design and analysis function needs to be brought on board. If a fabricator such as an HRSG Manufacturer is interested the venture may be expanded to include fabrication and assembly. This later option may be necessary for existing plant retrofits.

The product will be the license of the use of the technology including up-front analysis and design for the users. A one half percent performance improvement translates into a Present Value addition of $4,000 per installed MW. Value added modifications can be sold for about 50% of the present value if the payback is in the two to three year time frame. An F class turbine will produce and additional cash flow of over $200,000 for .5% gain in efficiency which is well within the cost of an E-D device.

The most likely potential customers are plant owners, HRSG manufacturers, or turbine manufacturer/packagers. The plant owners of both new and operating plants are the chief beneficiary of the technology and will be marketed extensively. HRSG manufacturers are the most logical clients for large frame engines in that their hardware is what will be modified to take advantage of this technology. Prepackaged units such as the Aero-derivative units would most likely incorporate the technology as a part of the package.

The installed capacity for gas turbines in the domestic market is over 100,000 MW of which at least 200 large frame turbines that are potential units for retrofit. The new turbine market is of the order of 7,000 MW that represents 30 large turbines a year. Thus the total market for existing turbines is $100 million and for new turbines is $15 million per year.

The product is simple and the patent has only three elements which means it will be hard to build around. If anything it is a much stronger shape than the traditional square transition section it would replace and the reduced turbulence down stream will improve the overall structural integrity of the HRSG.

Project Objectives

Objective 1: Demonstrate a reduction in backpressure at the gas turbine exit plane of 4 inches of water with the Ejector-Diffuser over a conventional turbine to HRSG transition section using Computational Fluid Dynamic Analysis (CFD)

Objective 2: Demonstrate the potential for stabilizing the boundary layer in the transition section of the HRSG by using the Ejector-Diffuser for boundary layer sucking to get the flow to turn the corner of the upper section of the transition section before it separates.

Objective 3: Demonstrate an overall improvement in efficiency of .5% or more

Project Approach

Task 1: Define the Standard Configuration
Select an existing Turbine/HRSG configuration and define the steady state parameters and geometry to be used.

The configuration chosen was an installation in Tiverton, Rhode Island consisting of a G. E. Frame 7FA Gas Turbine and a Nooter/Eriksen HRSG. (Figure 1)

The steady state conditions are:

GT Exhaust Flow Rate	3,594,572 lbm/hr
GT Exhaust Total Temp	1115 F
Pressure Drop Though HRSG	15.3 inches of water

Task 2: Setup & Run Standard Configuration
Create CAD model; Create CFD Mesh; specify fluid properties, boundary conditions, solver parameters, etc.; run CFD code; post processing.

Task 3: Setup & Run 1st E-D Configuration
Same as Task 2 with 1st E-D Configuration

The first Ejector-Diffuser (E-D) configuration is shown in Figure 2. A large plenum chamber with a bell-mouth Inlet to a diffuser well down-steam from the nozzle exit replaces the conical nozzle extension. The diffuser transitions from a round to square attachment to the HRSG Transition piece.

Task 4: Setup & Run 2nd E-D Configuration
Same as Task 2 with 2nd E-D Configuration

The bell-mouth inlet to the diffuser was removed and the diffuser inlet was moved well upstream such that the inlet was three feet down stream from the 7FA nozzle exit. (Figure 3)

Task 5: Setup & Run 3rd E-D Configuration with boundary layer control
Same as Task 2 with 3rd E-D Configuration

The next iteration involved examining the effects of introducing a feedback loop by utilizing the pressure differential between the HRSG transition and the E-D plenum. A box with an opening into the transition section was connected to the plenum by two ducts. (Figure 4) The objective was to see if the flow could be induced to turn the corner to smooth out the flow to the HRSG.

Task 6: Setup & Run 4rth E-D Configuration with boundary layer control
Same as Task 2 with 4th E-D Configuration

There was no 4th configuration run

Task 7: Perform reporting requirements (Progress Reports and Final Report)

Project Outcomes

The Base Line case has flow separation in the nozzle extension with the majority of the flow hugging the HRSG transition section along the floor. (Figures 5 & 6) The pressure profile at the Frame 7FA nozzle exit plane shows a spread of 0.15 psi which the result of the flow separation. (Figure 7) The pressure profile at the HRSG Inlet plane shows a significant spike along the lower portion demonstrating the effect the flow ramming into the first stage of the super-heater. (Figure 8)

The first E-D case, EjectF, had results quite similar to the Base Line case. (Figures 9 & 10) The flow did not attach itself to the bell-mouth, which is essential for the ejector to function. A slight bit of improvement is seen in the pressure spread at the nozzle exit plane and the HRSG Inlet plane. (Figures 11 & 12)

The first major improvement was seen with EjectF5, which was described Project Approach and illustrated in Figure 3. The flow is full in the diffuser with minor back-flow on the top section. (Figures 13 & 14) The nozzle exit plane static pressure is about 0.15 psi lower than the base case and the pressure profile at the HRSG Inlet Plane is very smooth. (Figures 15 & 16) The decreased pressure at the nozzle exit plane of 0.15 psi is about 4 inches of water.

The last iteration was EjectF6. (Figure 4) The flow characteristics are similar to EjectF5 with a small but noticeable improvement in the top section of the diffuser. (Figures 17 & 18) The static pressure at the nozzle exit plane and the HRSG Inlet are also similar. (Figures 19 & 20)

Conclusions

A properly designed Ejector-Diffuser can significantly improve the flow characteristics into the transition duct of a combined cycle gas turbine / HRSG assembly. The diffuser increases the adiabatic expansion ratio by a factor of 2. This allows the nozzle exit plane to decrease by about 4 inches of water.

The addition of a suction surface on the upper wall of the transition section does cause the upper surface of the diffuser to flow full. More work is required to investigate whether the flow can be induced to turn the corner.

The GE Frame 7FA efficiency is sensitive to nozzle exit plane pressure. A 4-inch drop in exit pressure will produce a 0.5 percent increase in efficiency.

Because the flow is so much smoother, the use of mechanical attenuators in the transition section will be reduced with an attendant decrease in pressure drop further improving the efficiency.

While this study looked at a combined cycle plant the E-D device will work equally well in a simple cycle installation.

The compactness and simplicity of the E-D should make the attractive for both new and retrofit markets.

Recommendations

A physical demonstration is required before significant interest can be generated. A cold test in a model test facility would be the first level. A simple cycle sea level hot test should follow. With successful results, the E-D is ready to move into stage four development.

Public Benefits to California

A more efficient plant cycle directly equates to a reduction in the amount of fuel required per KW. This is a benefit to the environment. In an unregulated market, competition should force some of the savings into the price structure.

Development Stage Assessment

Marketing

There is a clear market for this product. There is no direct competitor to this product. The closest technology is the "Flow Enhancer" designed by Consultants in Engineering Acoustics used on the LM2500 series Gas Turbine generator sets. However this is a complex set of engineered shapes installed in the turbine exhaust collector box designed to soften the insult of the 90° turn which the exhaust takes within one diameter of the turbine nozzle. This is successfully marketed to plant owners for $5,000 per installed MW. This is a good indication that efficiency will sell and with the deregulated market where market share is becoming cost driven, efficiency becomes even more important. This technology, while proven, is still meeting resistance because of the concerns of introducing complex materials in the gas stream, which could potentially come loose and cause foreign object damage.

Engineering/Technical

The Ejector-Diffuser is a very simple structure with the only variable being the diffuser diameter. Finding the correct diameter is a straightforward CFD exercise.

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Legal / Contractual

The E-D application to the power industry is patented. (Patent No. 5,632,142) A trial license agreement was negotiated with an HRSG manufacturer.

Risk Assessment / Quality Plans

The investment needed to demonstrate the effectiveness of the E-D is a hot fire test of an axial flow gas turbine. The continuing operating investment would be limited to design, fabrication and installation of a product that is well within the state of the art of any steel fabricator.

Strategic

This is a stand alone product that has no critical dependence to other programs

Production Readiness

As stated above, fabrication of this device is standard practice for any boiler manufacturer.

Public Benefits / Costs

Economical efficiency improvement is assured by the rapid payback

Appendices

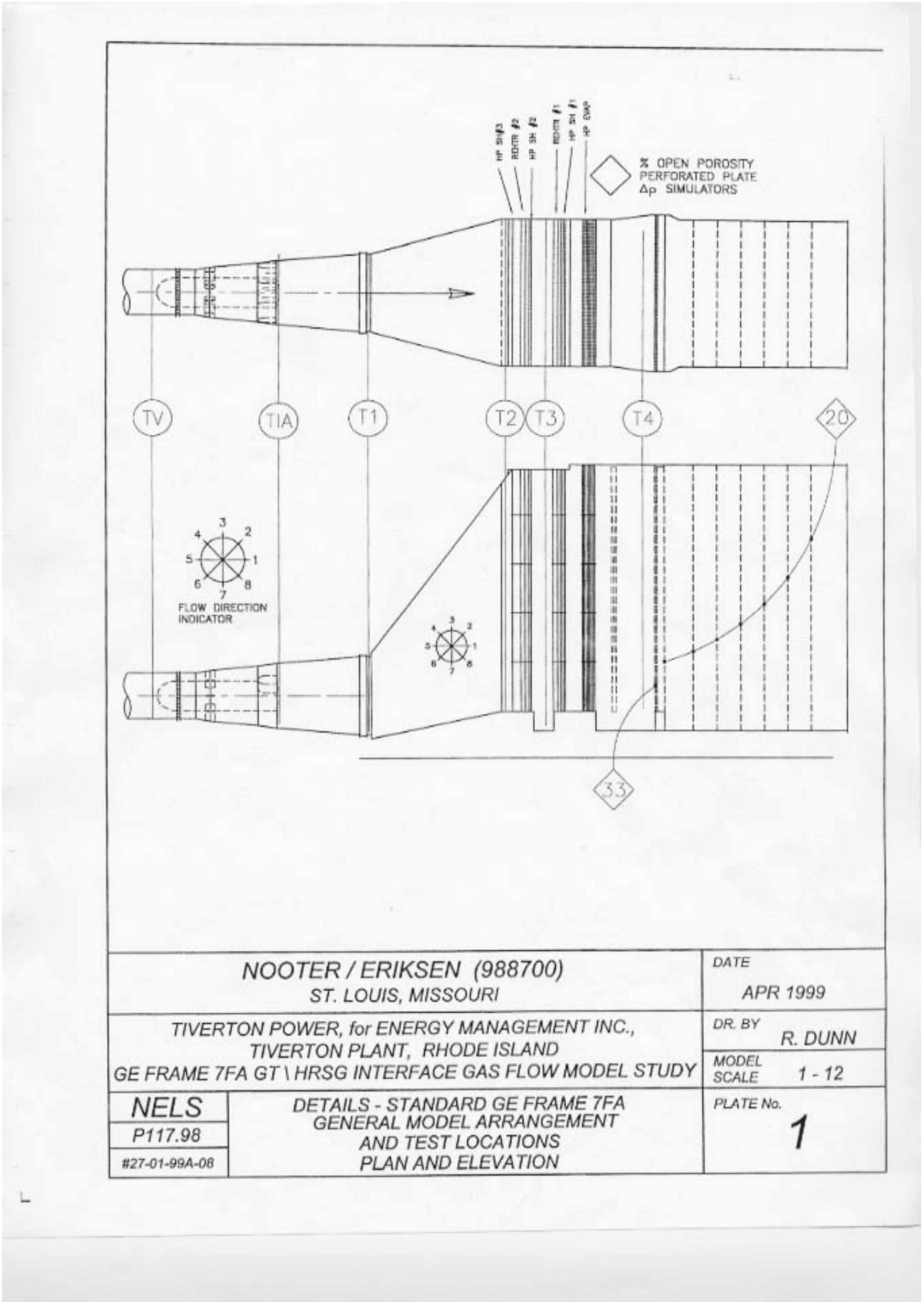

Figure 1: Base Case Configuration

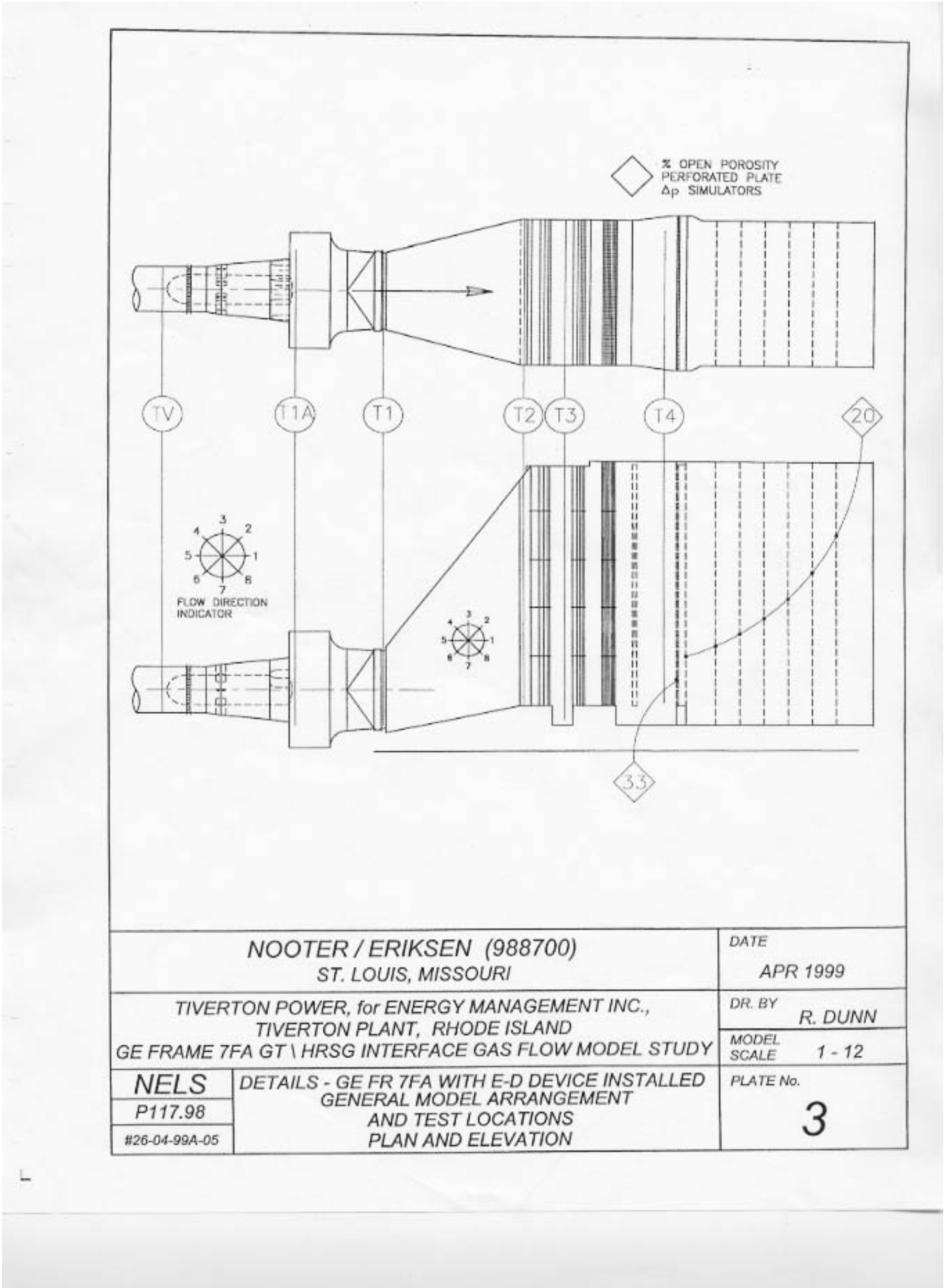

Figure 2: EjectF Case Configuration

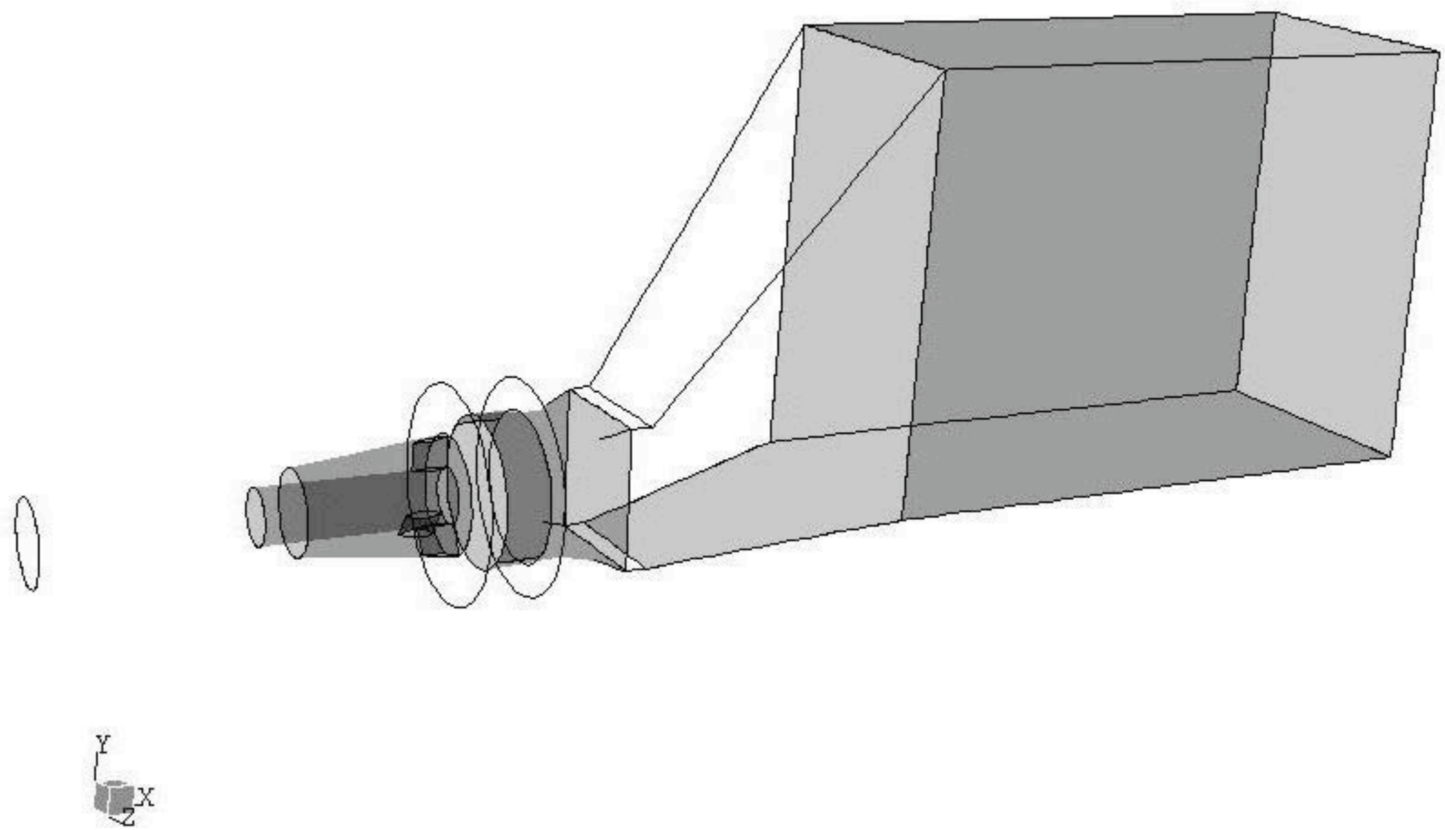

Figure 3: EjectF5 Case; Tubine Nozzle and Ejector Diffuser Arrangment

CFX

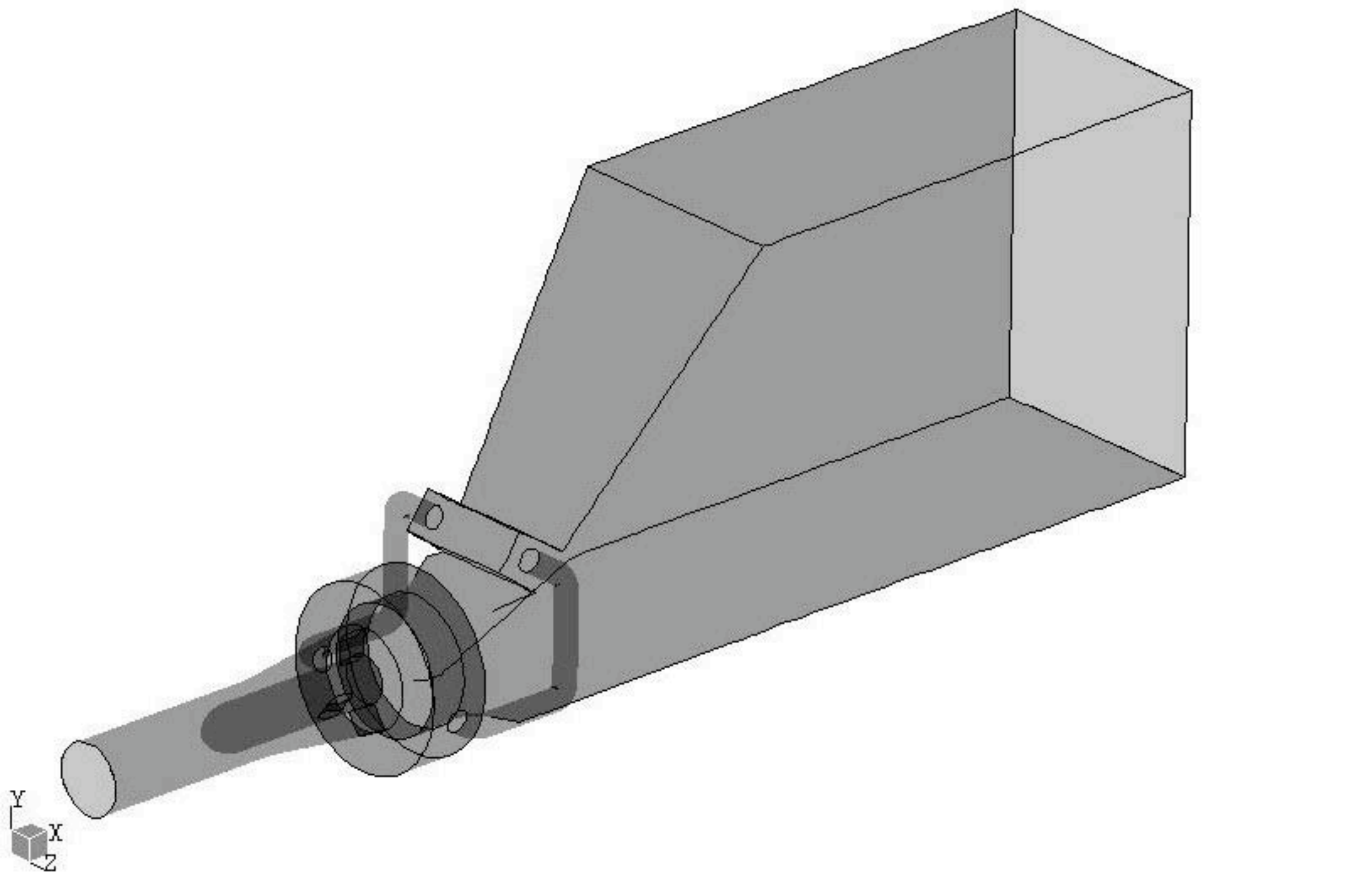

Figure 4: EjectF6 Case; Suction Surface with Feedback Piping

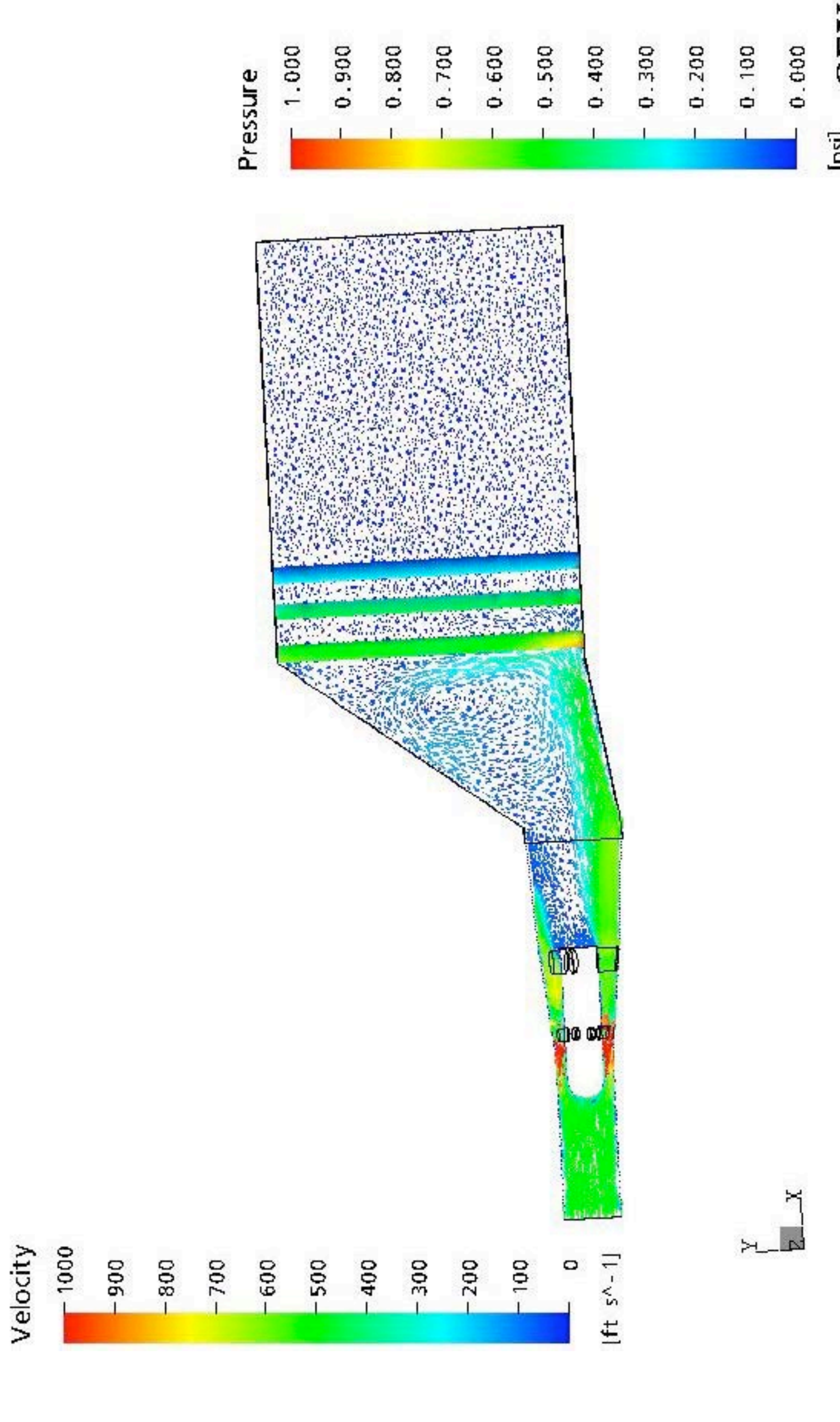

Figure 5: BaseF Case; Velocity Vectors & HRSG Pressure Drop Through Tube Elements

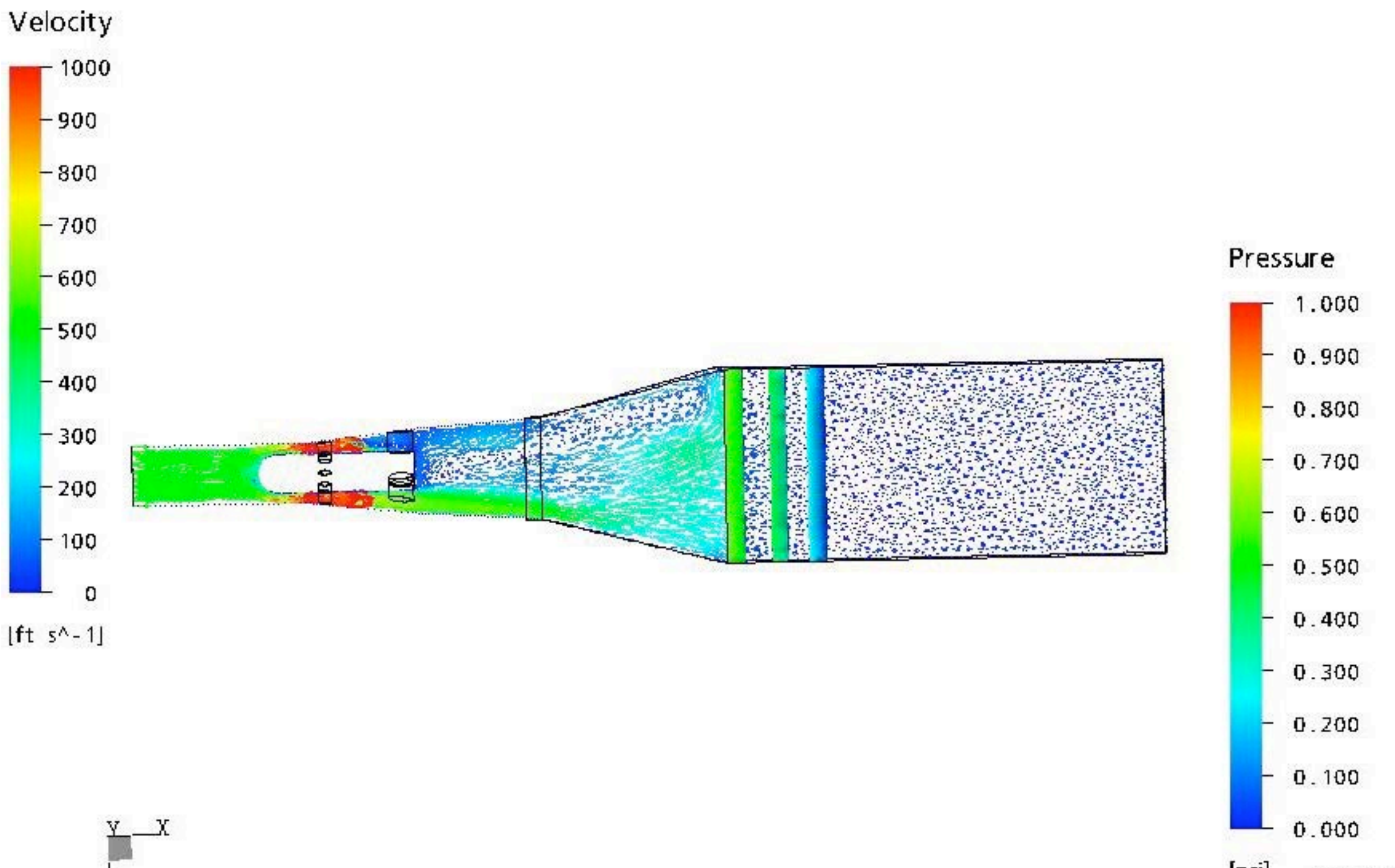

Figure 6: BaseF Case; Velocity Vectors & Pressure Drop Through Tube Elements

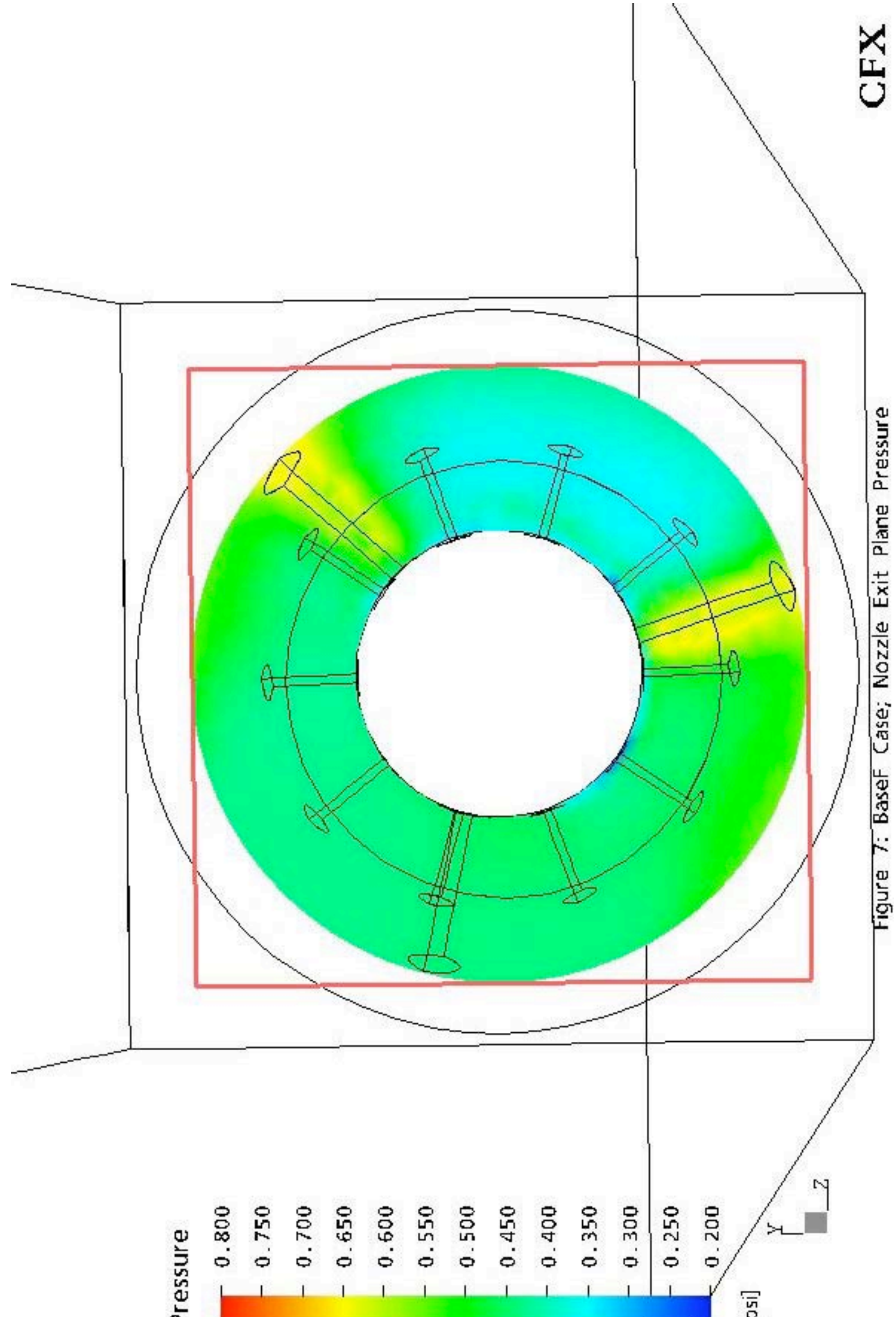

Figure 7: BaseF Case; Nozzle Exit Plane Pressure

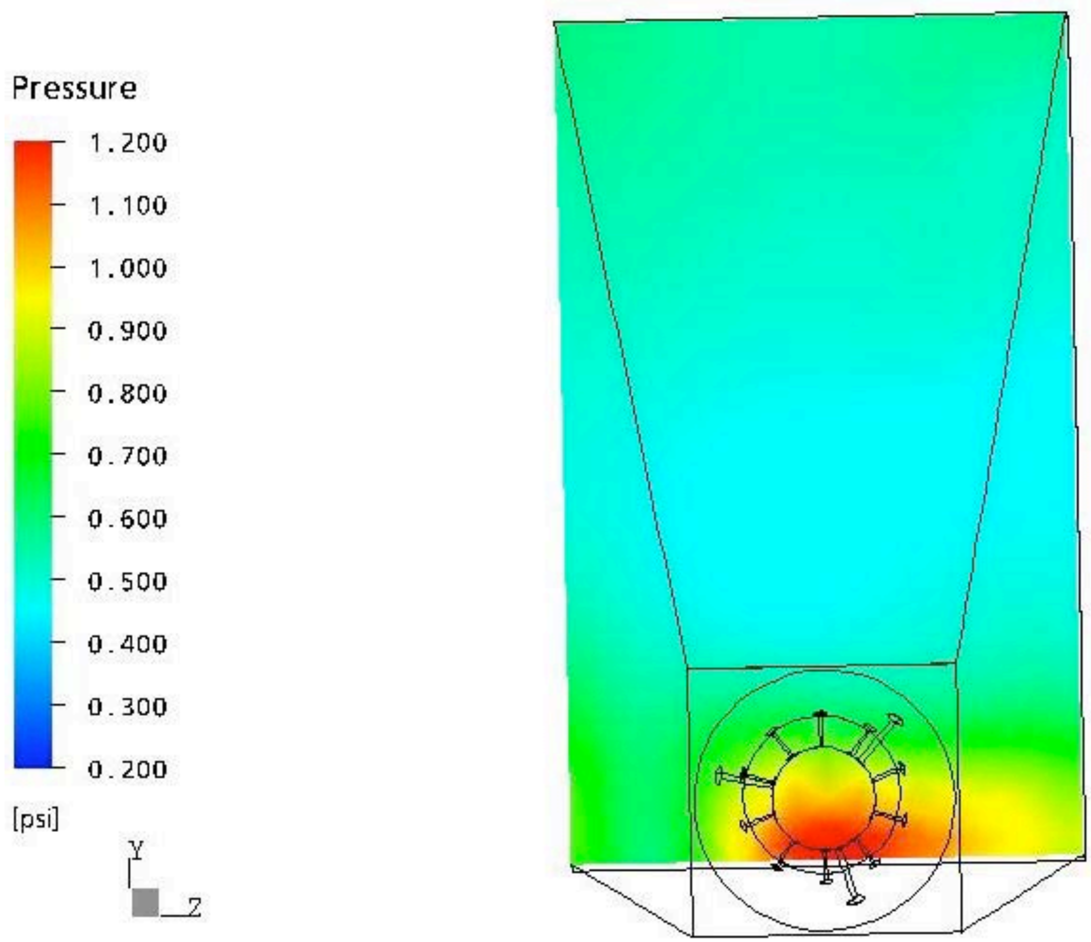

Figure 8: BaseF Case; Hrsg Inlet Pressure

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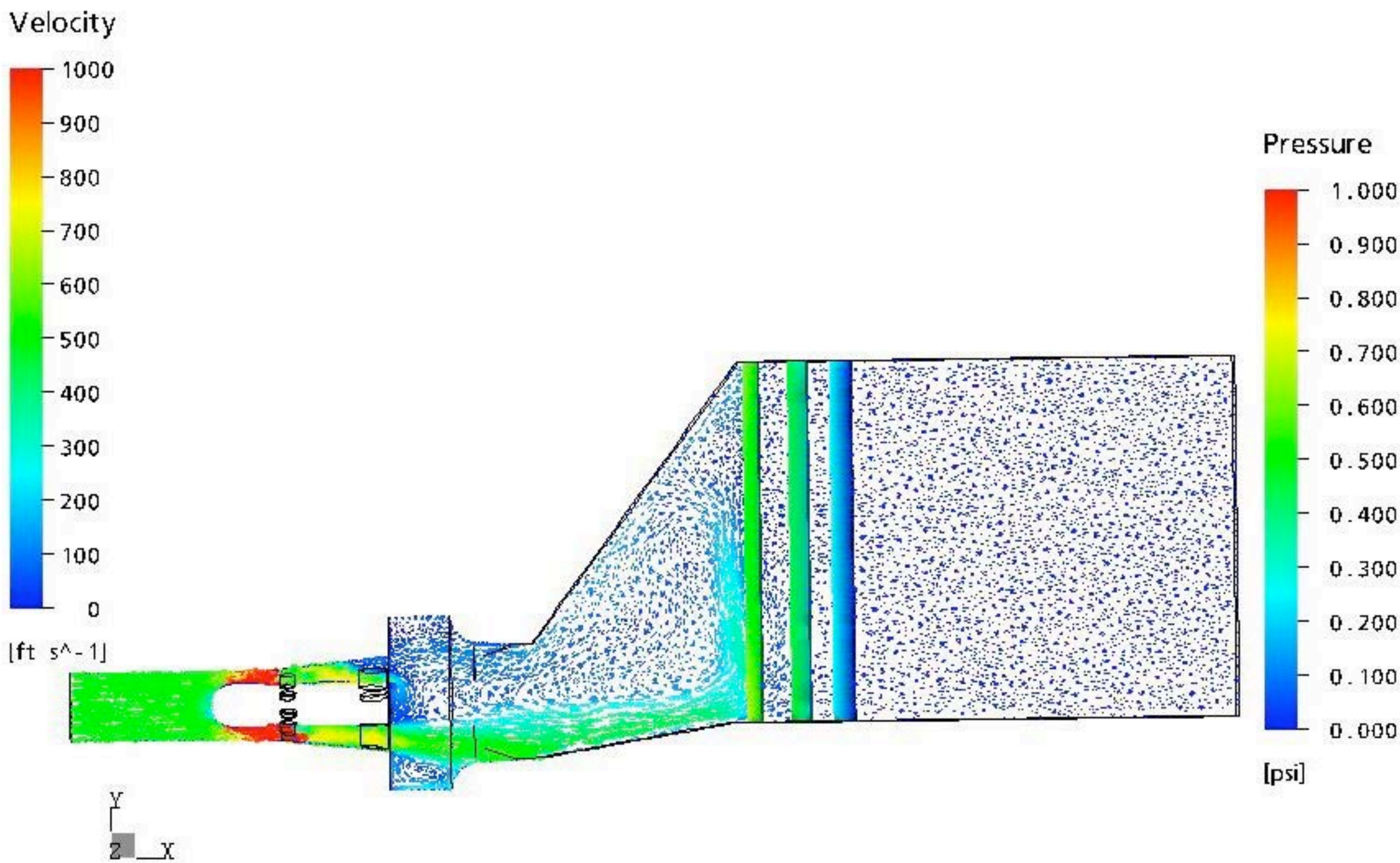

Figure 9: EjectF Case; Velocity Vectors & Pressure Drop Through Tube Elements

CFX

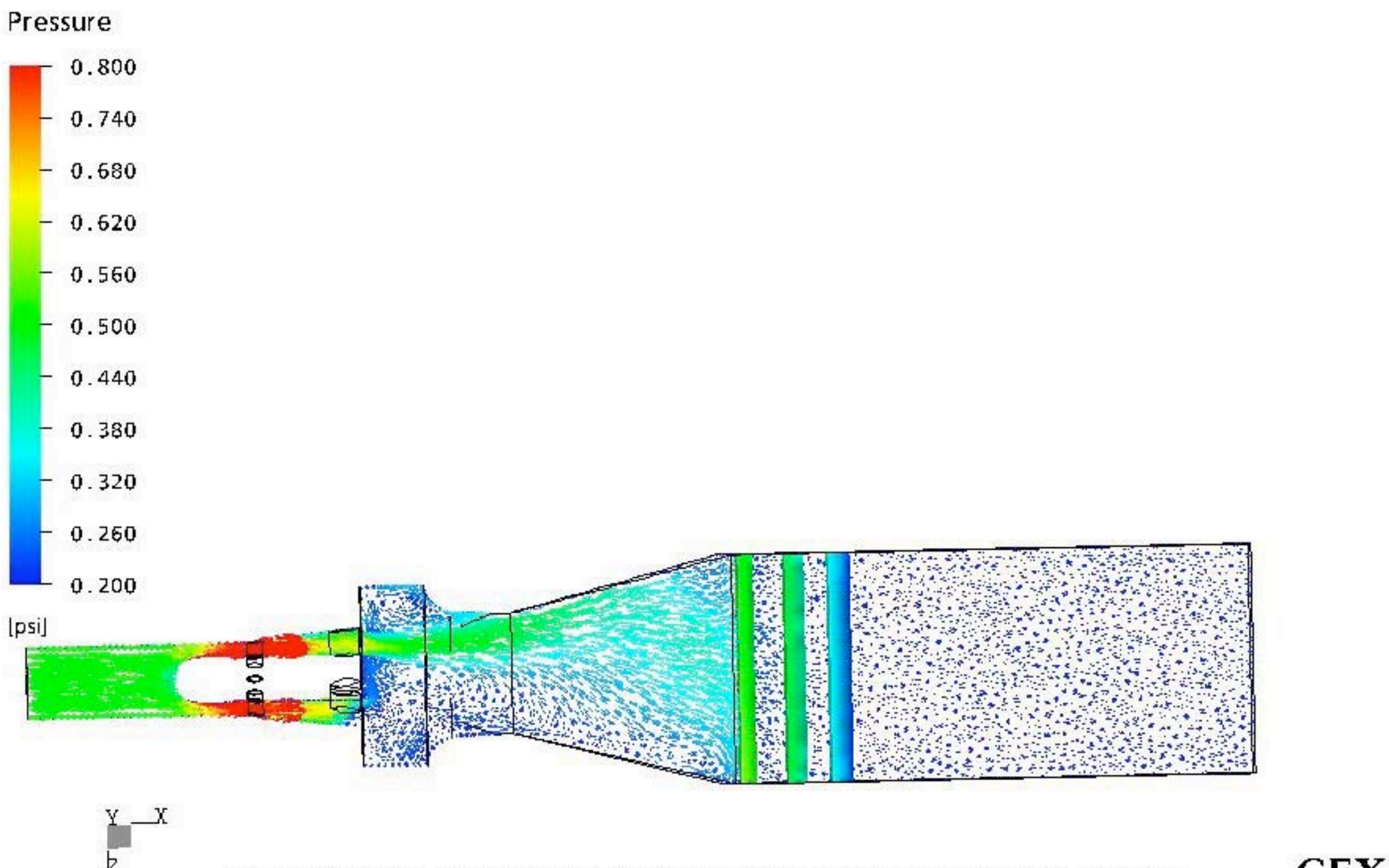

Figure 10: EjectF Case; Velocity Vectors & Pressure Drop Through Tube Elements

X

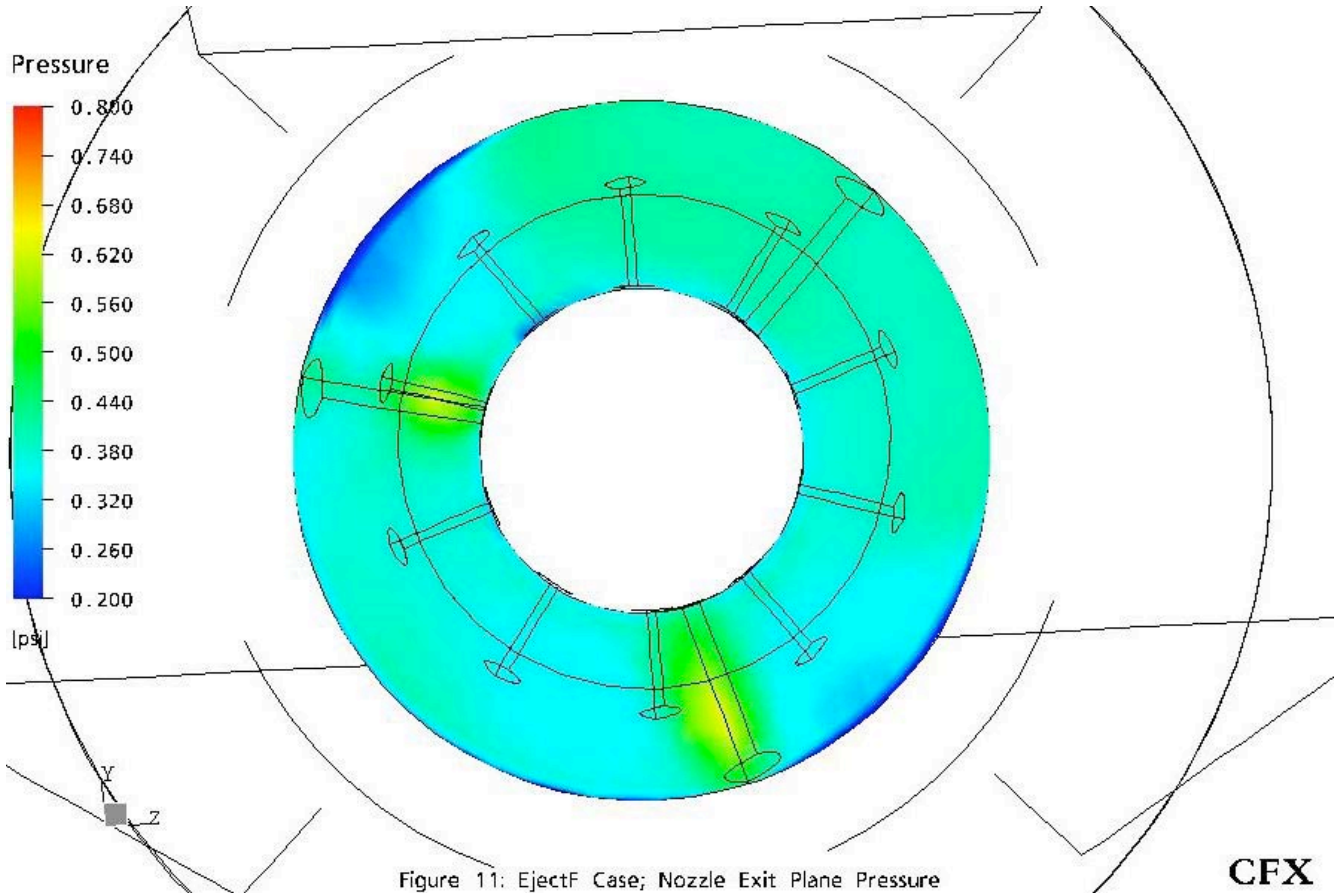

Figure 11: EjectF Case; Nozzle Exit Plane Pressure

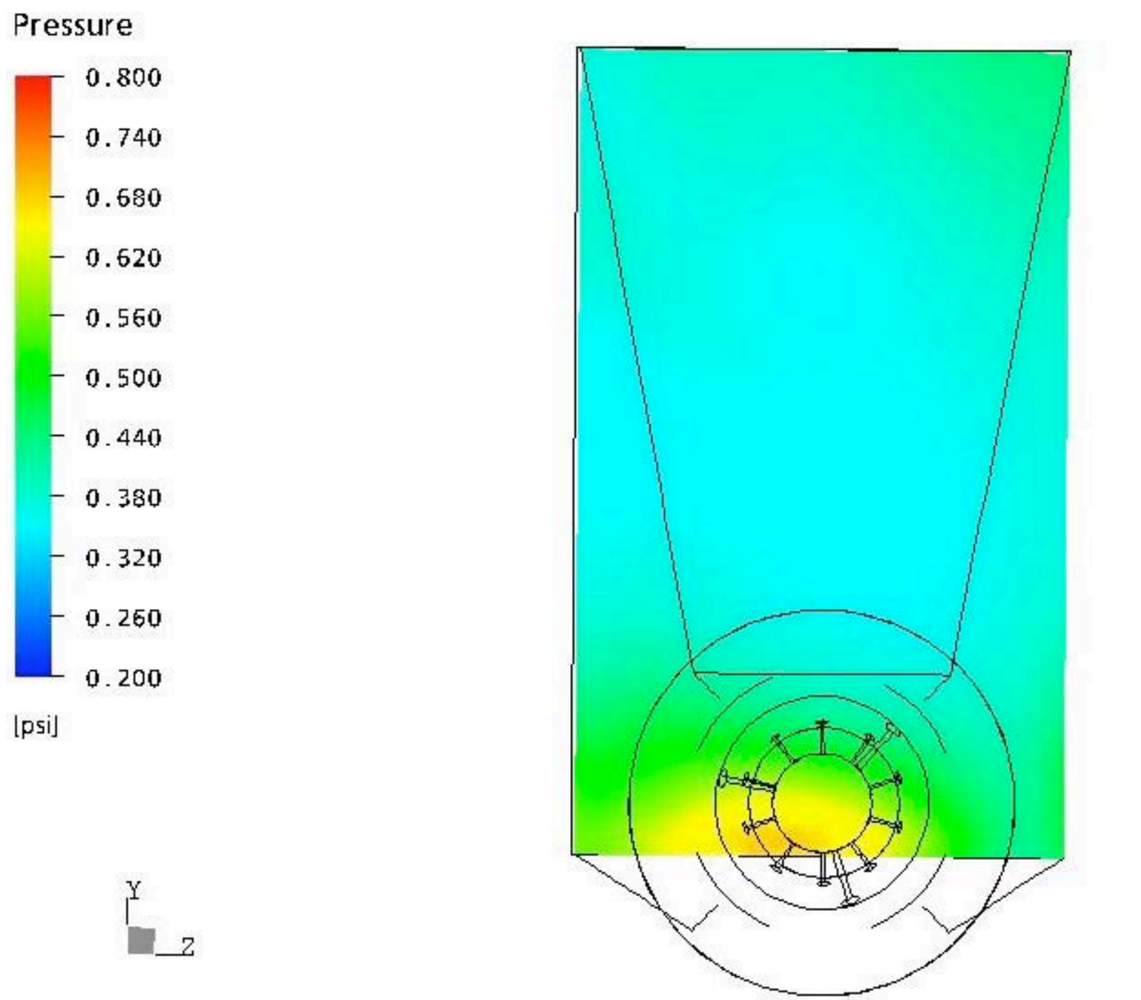

Figure 12: EjectF Case; HRSG Inlet Plane Pressure

CFX

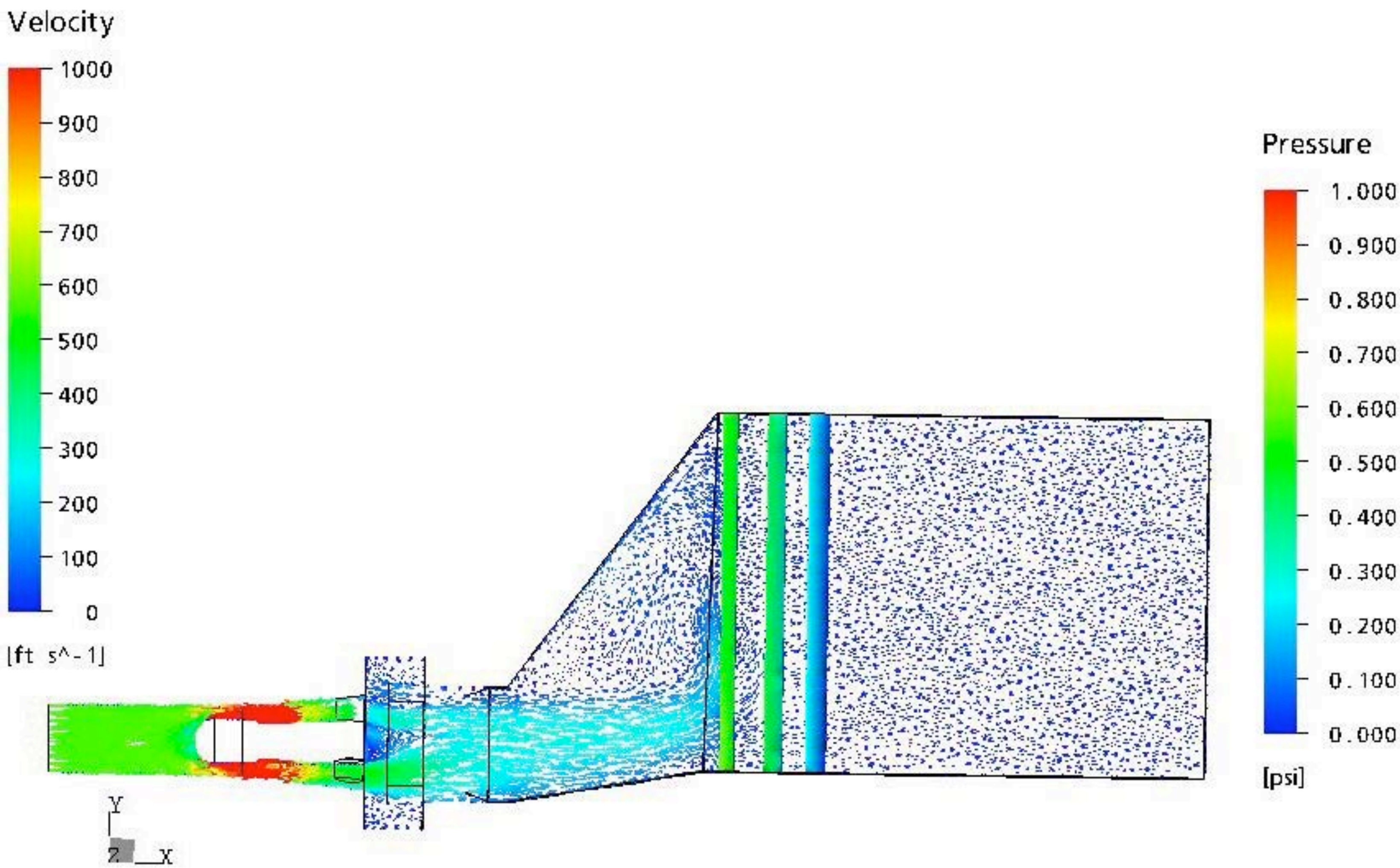

Figure 13: EjedtF5 Case; Velocity Vectors & HRSG Pressure Drop Through Tube Elements

CFX

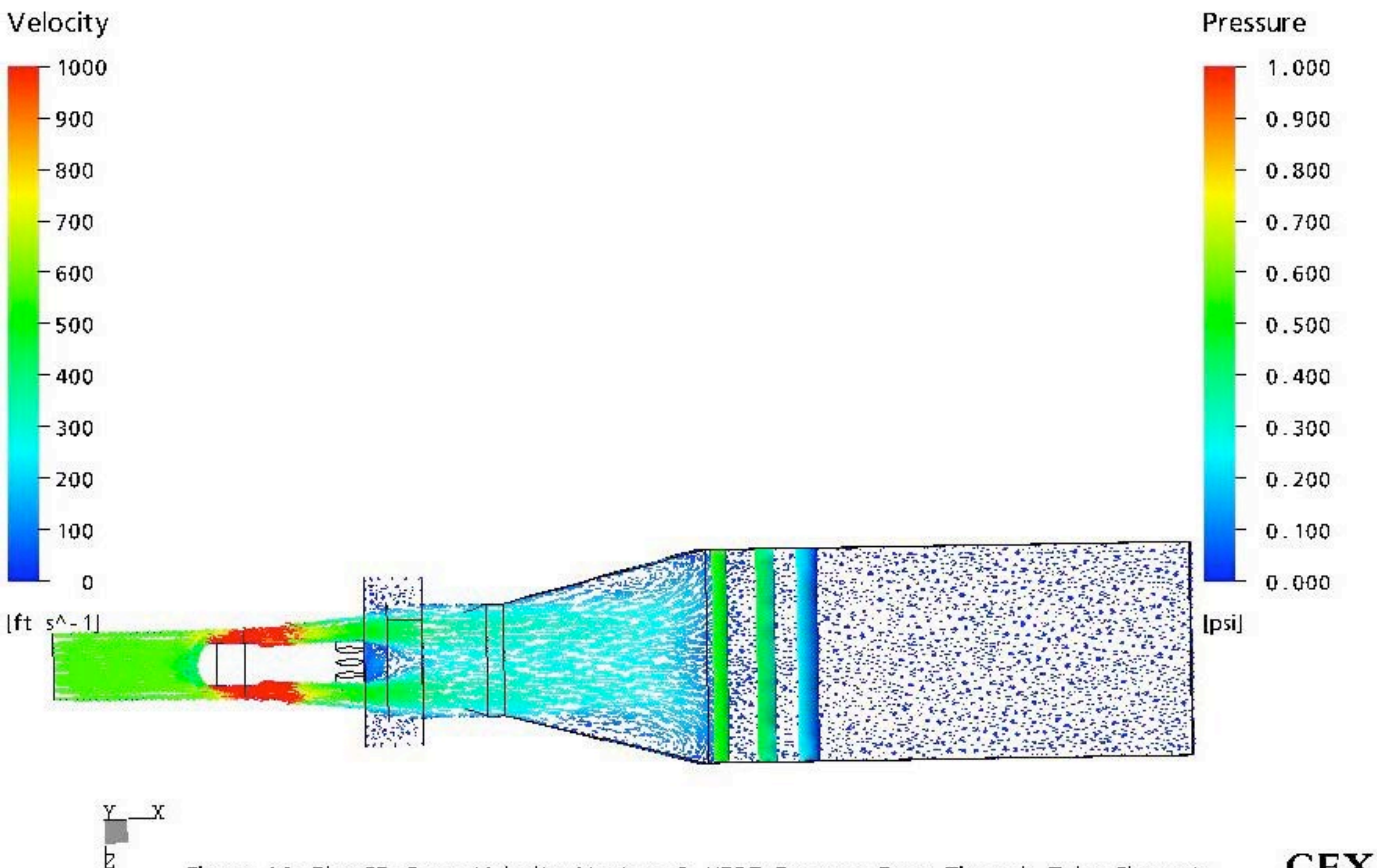

Figure 14: EjectF5 Case; Velocity Vectors & HRSG Pressure Drop Through Tube Elements

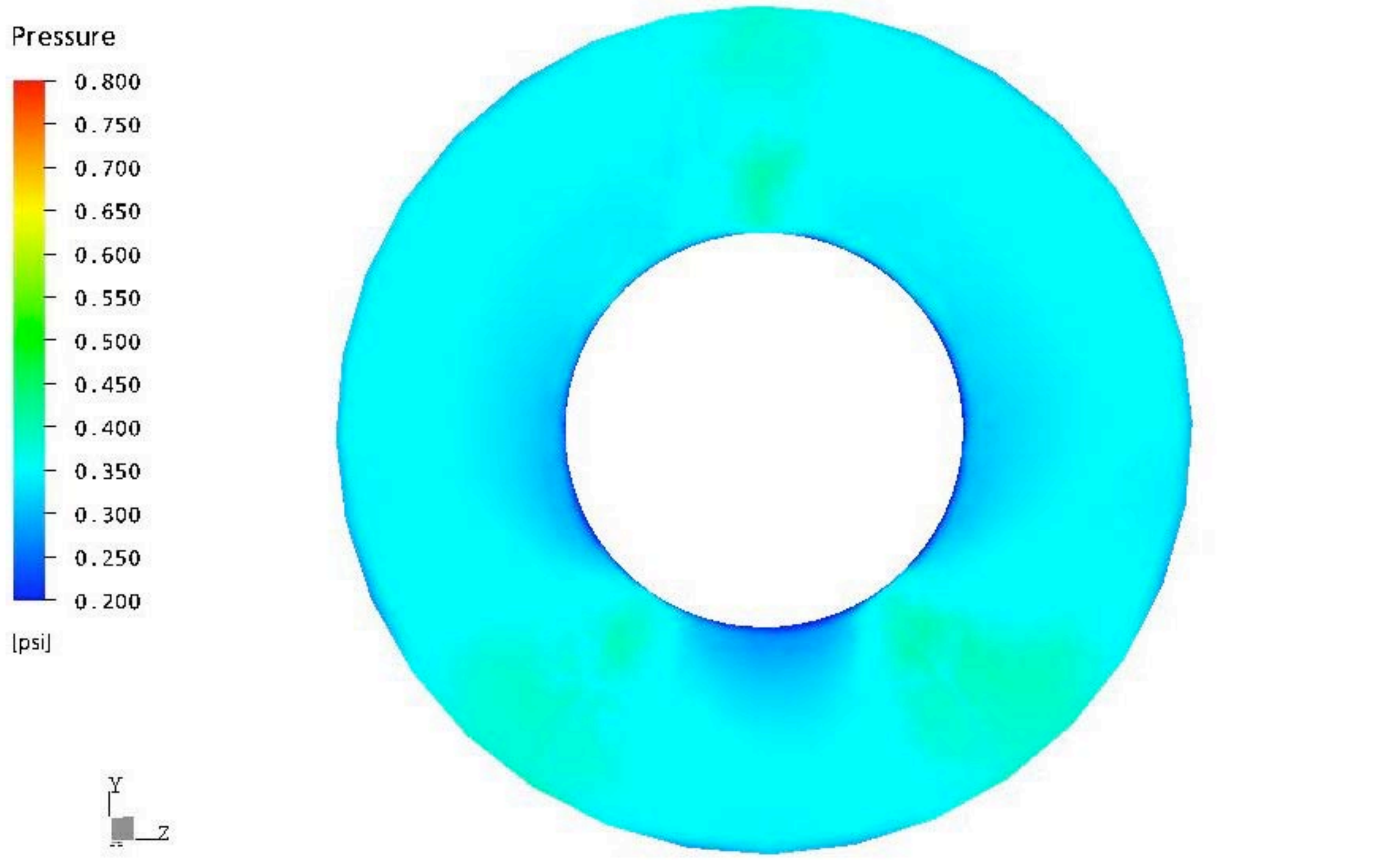

Figure 15: EjectF5 Case; Nozzle Exit Plane Pressure

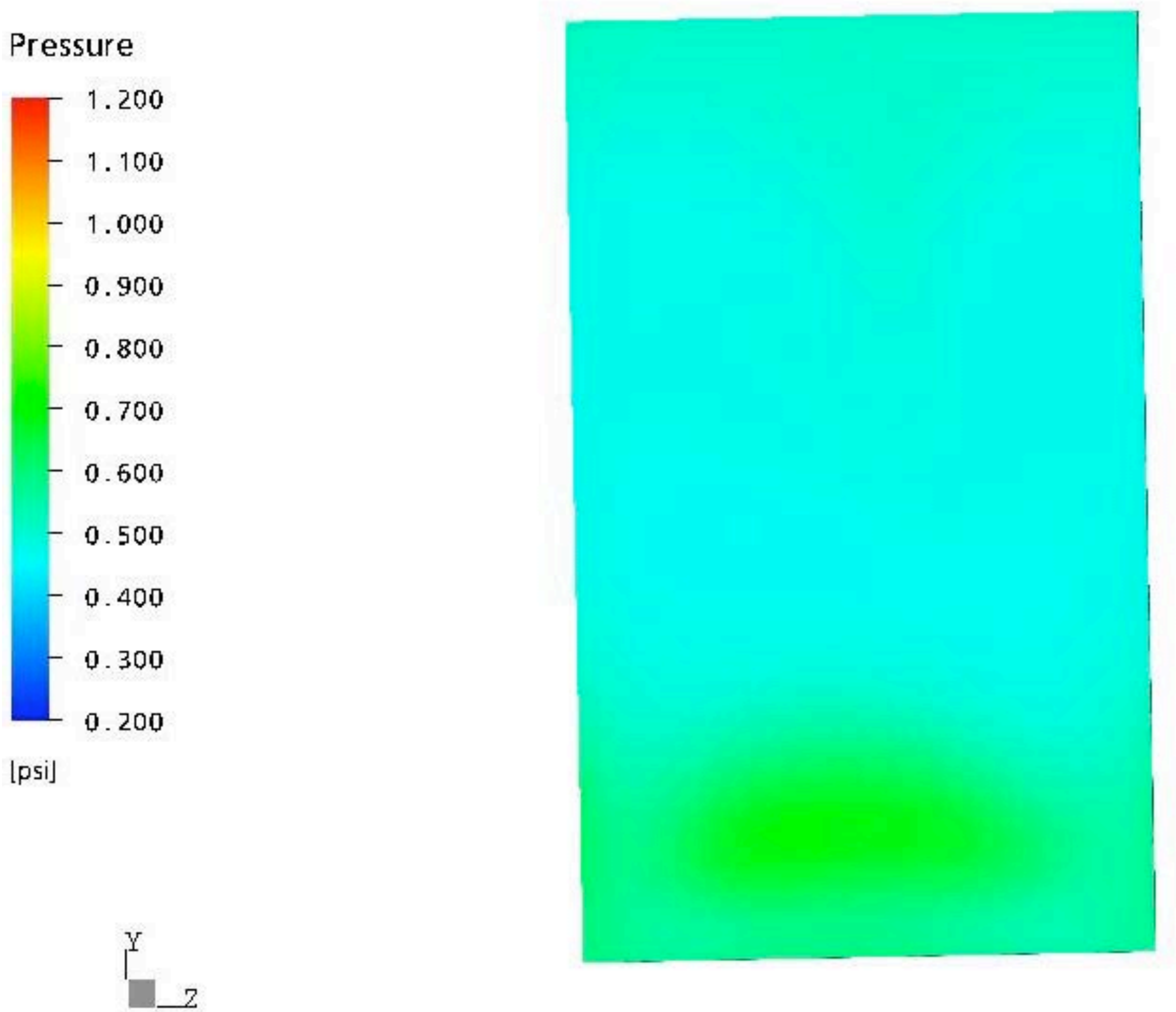

Figure 16: EjectF5 Case; HRSG Inlet Pressure

CFX

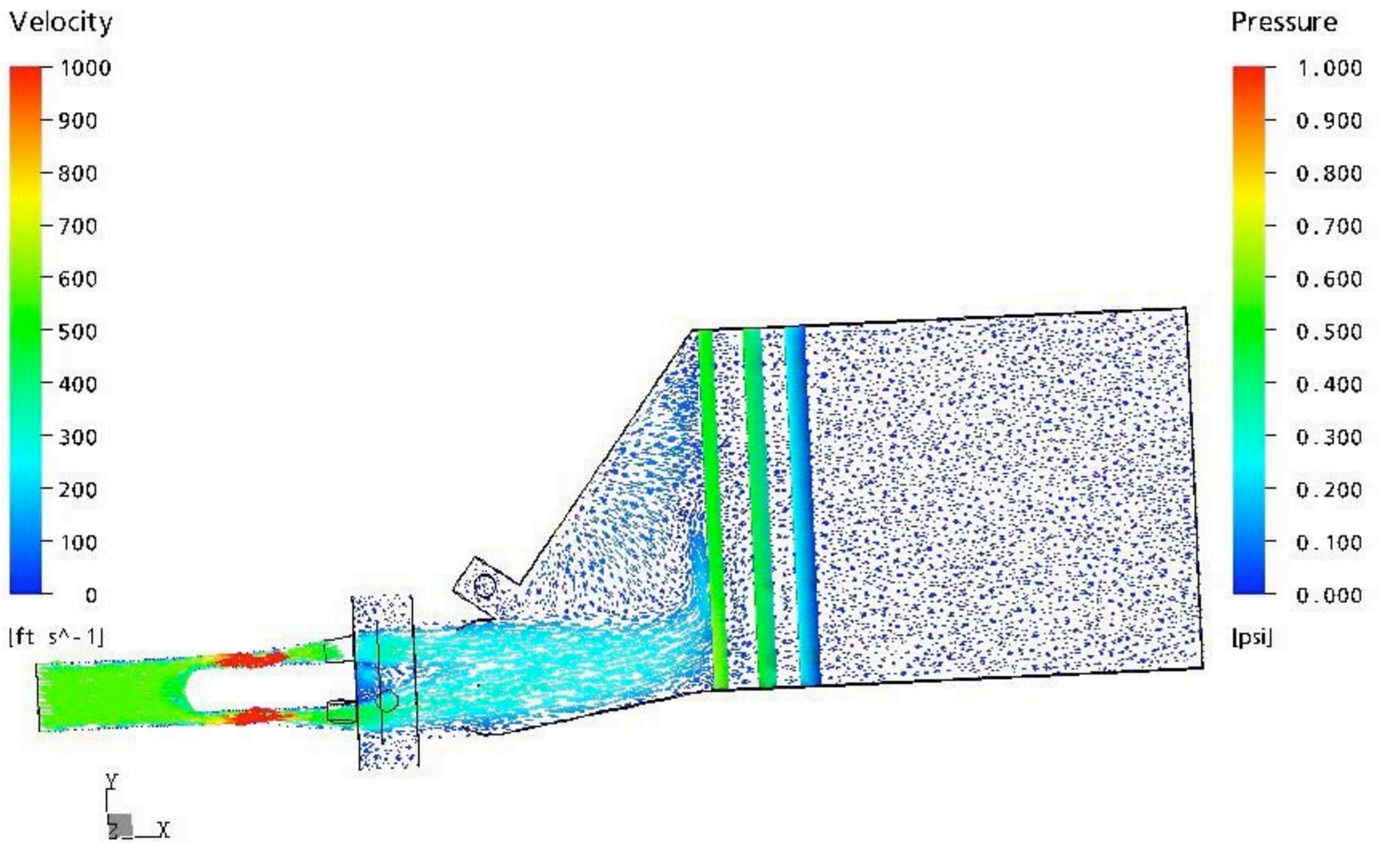

Figure 17: EjectF6 Case; Velocity Vectors & HRSG Pressure Drop Through Tube Elements

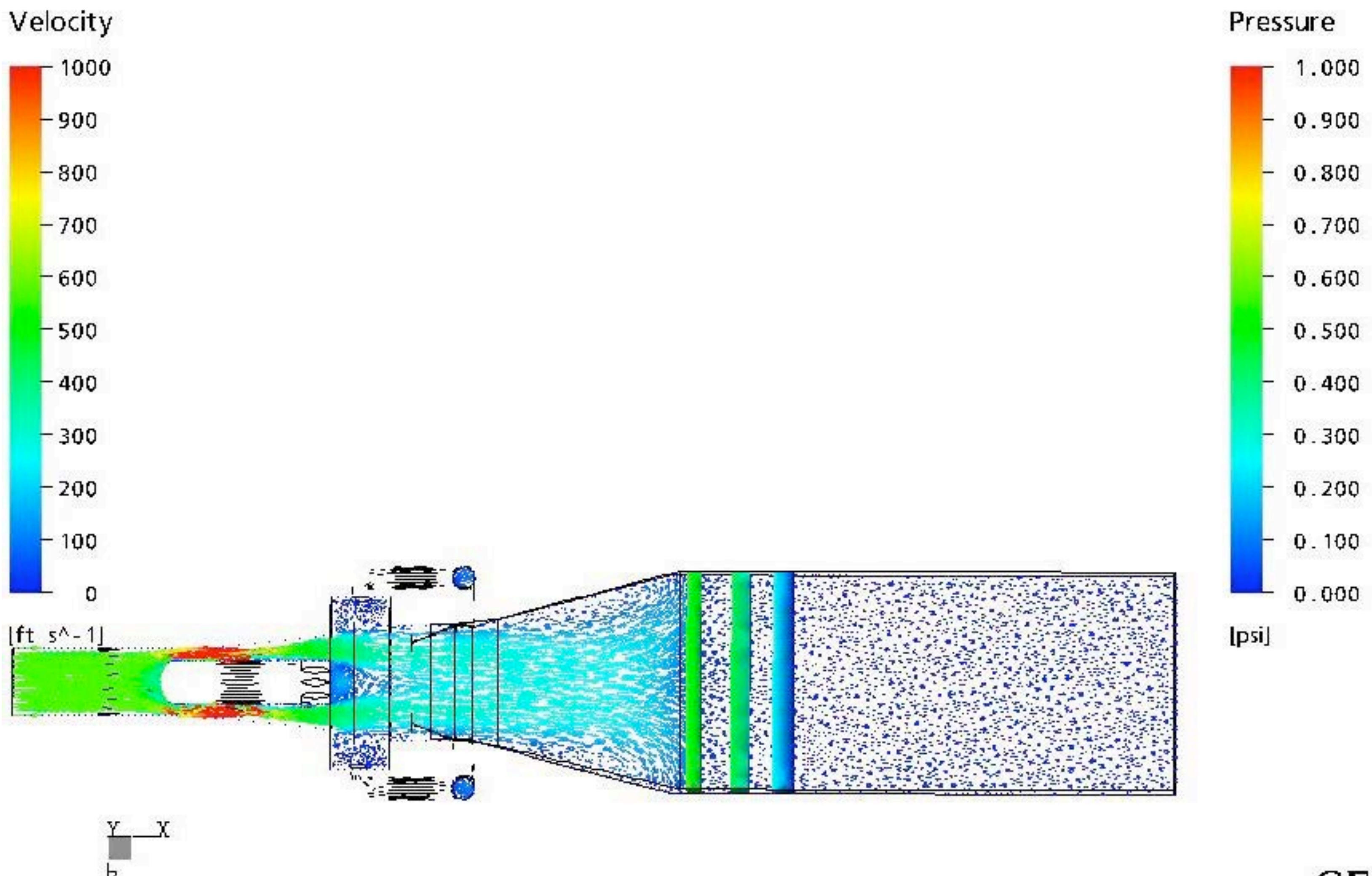

Figure 18: EjectF6 Case; Velocity Vectors & HRSG Pressure Drop Through Tube Elements

CFX

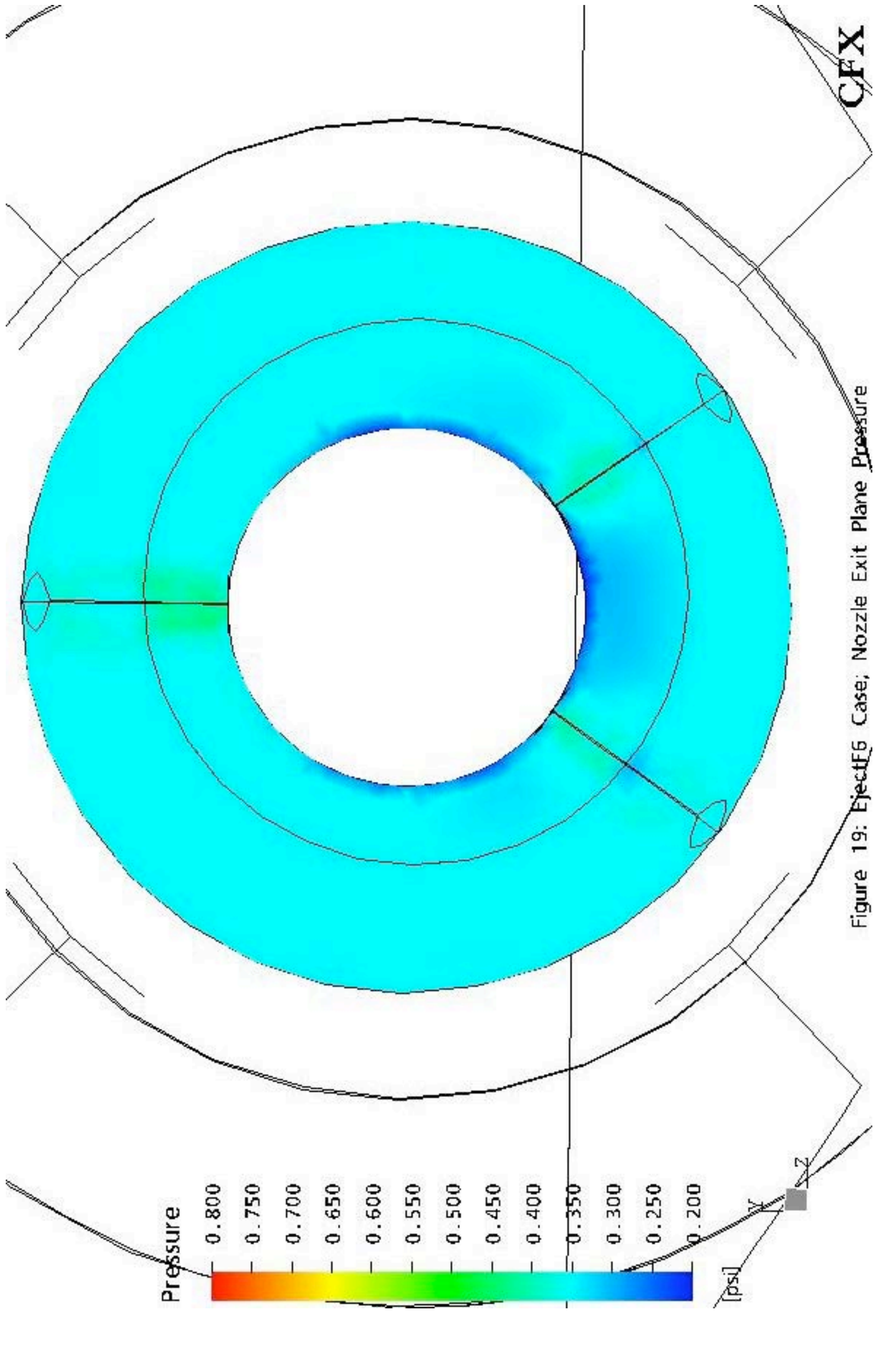

Figure 19: EjectF6 Case; Nozzle Exit Plane Pressure

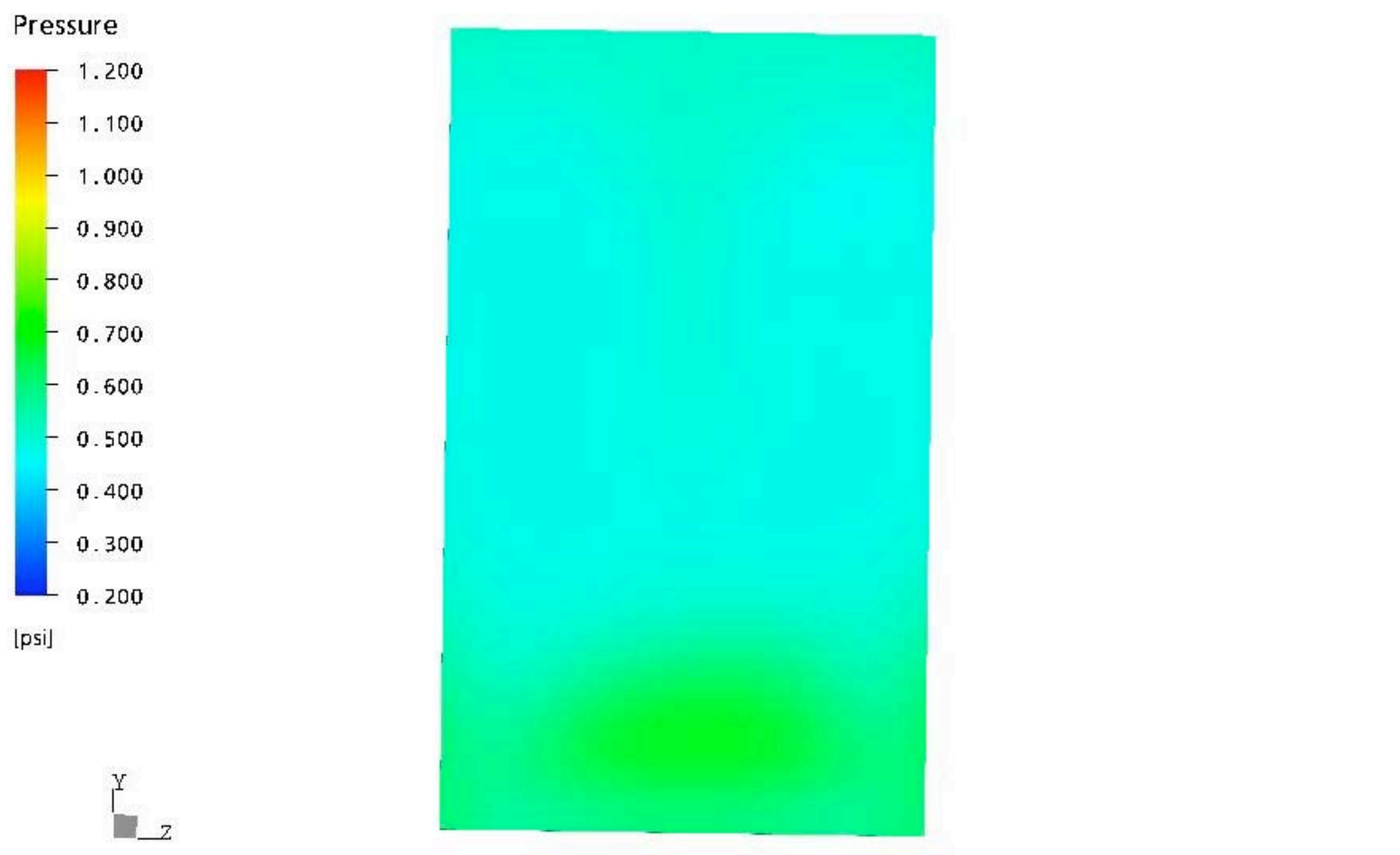

Figure 20: EjectF6 Case; HRSG Inlet Pressure